Parametric Optimization of Solar Assisted Bioreactor

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***Abstract*-This study involves utilization of solar energy through the use of the solar collectors combined with the heat exchanger to keep the digestor at the optimum temperature throughout the year. The thermal and economic analysis of 2m^3 solar heated biogas plant has been carried out and the effect of operating parameters on commulative solar savings is investigated. This is done by calculating the losses from the digestor and compensating these losses by using solar energy. Investigation has been carried out on the thermal and economic aspects of solar heated biogas plant to arrive at the optimal size of solar system. A design procedure has been proposed to arrive at the optimum value of solar collector area. It was concluded that increasing collector unit cost results in decreasing commulative solar saving. Plots have been prepared to represent the optimum solar collector area.**

Keywords-Biogas production, solar energy application, Thermal analysis, Economic analysis

NOMENCLATURE

M_s mass of slurry (kg) feed into digestor
C_s specific heat of the slurry (J kg^{-1} $^oC^{-1}$)
T_s temperature of slurry (^{o}C)
T_a ambient temperature (^{o}C)
U heat transfer coefficient from gas to ambient air (W m^{-2} $^oC^{-1}$)
A_t curved area of top surface of dome (m^2)
h_b heat transfer coefficient between slurry and ground through base and walls of digestor (W m^{-2} $^oC^{-1}$)
A_h area of base of dome (m^2)
T_∞ temperature of surface surrounding dome (^{o}C)
E_{Loss} loss from digestor in a month
A_w area of walls of dome (m^2)
k month number from January to December
i hours of the day from 6 AM to 6AM
T_w mean film temperature (^{o}C)
F' collector efficiency factor
A_c collector area of absorbing surface (m^2)
H_s solar intensity on absorber (W m^{-2})
($\tau\alpha$) transmittivity absorptivity product of collector absorber
d_l interest rate on loan
f_l fraction taken as loan
n CSS calculation period
i_m rate of increase in maintenance cost
M annual maintenance cost in Rs

I. INTRODUCTION

Biogas can be obtained from agro and animal wastes by anaerobic digestion. Community based biogas plants have been extensively used in most parts of India. Temperature is one of the key factors that affect the biogas production. Most digesters installed in the field lack mechanism for temperature control and removal of dissolved oxygen. Hence, efficiency of these digesters is reported to be low, particularly during the winter months. There are different temperature ranges during which mesophilic and thermophilic bacteria are most active causing maximum gas yield. Generally, mesophilic bacteria are most active in the temperature range 35-40°C and thermophilic bacteria in the range 50-60°C. Choice between the mesophilic and thermophilic fermentations is governed by the natural climatic conditions in which the plant is located. Though, it is possible to create conditions for thermophilic fermentation by external heat, but such a method is generally uneconomical. Length of optimum fermentation period is linked to the digester temperature. The methanogens are inactive in extreme high and low temperatures, while the optimum temperature is 25°C - 26^{o}C [1]. When the ambient temperature decreases to 10°C, gas production virtually stops. Satisfactory gas production takes place in the mesophilic range (30 - 40°C). Proper insulation of digester helps to increase gas production during the cold weather [1]. When the digester operates at a temperature of 15°C it takes nearly a year for the digestion cycle to complete. However, if the temperature is approximately 35°C, the cycle can be easily completed in less than a month [2]. When the digester temperature is maintained at 25°C, it takes approximately 50 days for digestion of cattle waste. But, if the temperature ranges between 32 and 38°C, digestion is complete within 28 days. Mahanta et al. [3] Carried out experiments to study the effect of temperature variation on anaerobic fermentation of cattle wastes. Smith et al. [4] suggested that at low temperature, biogas plants with some design modifications could also function quite effectively as in a warm climate.

Gupta et al. [5] described an improved solar assisted biogas plant of fixed dome type and carried out the transient analysis and proposed to use insulation at the base and walls of bioreactor. To assess the transient behavior of the slurry temperature they employed the data of ambient temperature

and solar radiation intensity in the coldest day of Delhi i.e. 26 January. They analyzed the effect of different variables (Number of collectors, length of pipe immersed in slurry, insulation, number of days, slurry mass) on slurry temperature.

Subramanyam [6] proposed solar heat to upgrade biogas plant performance. He considered salt gradient solar pond to ensure year round energy supply at low temperature without any fuel costs. A vapour condensation heat transfer system based on acetone (B.P. 55^{o}C) consisting of a sealed system in which two containers, one each in a biogas digester and solar pond connected by a sloping pipe was suggested.

Kocar and Eryasar [7] reviewed the solar heated biogas plants and optimized the insulation thicknesses and solar energy systems for 5 m^3 biogas reactor for two different cities and for three different climatic zones in Turkey. Based on the results, the ratio of annually produced biogas used for reactor heating was calculated for each city, with and without solar heating system. The results indicate that the biogas consumption for reactor heating is decreased by approximately 19% for average of six cities when solar heating system is used. This means that available biogas potential would be increased.

Taousanidis [8] evaluated the economic advantage in using a combisystem instead of a conventional one, calculating the difference between the overall costs of the two systems supplying the same amount of energy. It was found that only after the remarkable social and environmental benefits of solar energy replacing fossil fuel fired systems are introduced in the market competition, the solar combisystem may become more cost efficient than the corresponding oil or natural gas ones.

A solar heating system was proposed by Dai and Chun [9] with evacuated tubes with auxiliary electric heater to provide thermal energy to bioreactor. They proposed a system of solar collector combined with heat exchanger. They carried out the experimentation at 15, 20 and 25^{o}C of digestor temperature and found that the optimum temperature for biogas production was 25^{o}C.

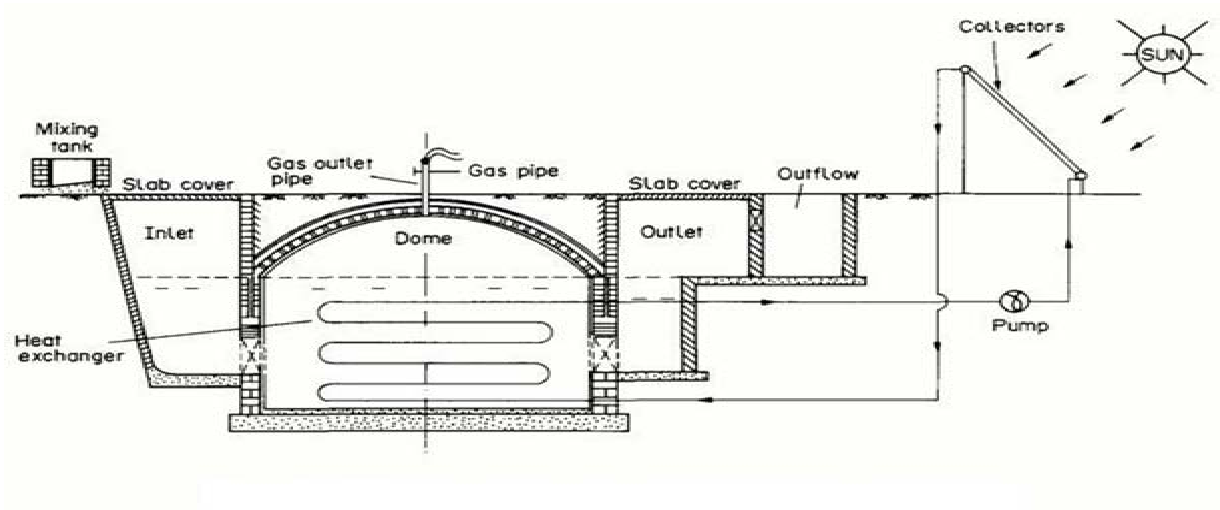

Fig 1: Solar Heated Biogas plant

Alkhamis and Kablan [10] proposed a solar heating system in which solar collector combined with a heat exchanger was used to heat the water jacket around the bioreactor. A proportional Integral Differential (PID) controller was installed to control the temperature at 40oC. The efficiency of collector was found to be around 61% .The controller action was seen to be very effective and a prompt response for a variation of 1K was noticed.

Vinoth and Kasturi [11] carried out a study with the objective of evaluating plastic as an alternative material for solar heated biogas plant. The results of controlled conventional Deenbandhu model were compared with the experimental results on digestor made from plastic with greenhouse canopy of similar capacity.

II. OBJECTIVE

It is well known that climatic conditions in India in winter are such that the biogas production is seriously affected. Use of solar energy to augment the biogas production is considered to be a viable option. However there is a need to determine optimum size of the solar collector system to suit the given biogas plant. In the present work, it is proposed to investigate the economic aspects of solar heated biogas plant to arrive at the optimal size of solar system. The following are major objectives of present study

- Thermal analysis of solar heated biogas plant.
- Economic analysis of the system.
- Optimization of solar collector area.

III. SYSTEM DESCRIPTION

The schematic diagram of proposed system is shown in Fig. 1. The system comprises of a biogas plant including the digester, gas holder, mixing and outlet tanks, gas outlet etc. and the solar heating system comprising of solar collectors, heat exchanger, pump and associated piping etc. The solar collector combined with a heat exchanger maintained the digestor at optimum temperature. If there is not enough solar radiation then the auxiliary heating will maintain the digestor at optimum temperature.

IV. THERMAL ANALYSIS

A. *Energy losses*

Energy loss from digester has the following components:

Energy lost due to feeding of slurry

$$E_1 = M_s\, C_s\, (T_s - T_a) \tag{1}$$

Energy lost from the top surface of dome

$$E_2 = U\, A_t\, (T_s - T_a) \tag{2}$$

Energy lost from the base

$$E_3 = h_b\, A_h\, (T_s - T_\infty) \tag{3}$$

Energy lost from the side walls of digester:

$$E_4 = h_b\, A_w\, (T_s - T_\infty) \tag{4}$$

Assume the temperature of ambient air and surface surrounding dome are same, i.e. $T_a = T_\infty$

Total loss from the digester in 24 hours is the sum of the above losses

i.e. $E_{Loss} = E_1 + E_2 + E_3 + E_4$, which can be written as:

$$E_{Loss} = [M_s C_s (T_s - T_a) + \sum_{i=1}^{i=24} UA_t\,(Ts - T_a(i)) + h_b A_h\,(T_s - T_\infty(i)) + h_b A_w\,(T_s - T_\infty(i))] \tag{5}$$

The total loss for the year is the sum of the losses for every month

$$E_{Total\ Loss} = \sum_{k=1}^{k=12} E_{Loss}\,(k) \tag{6}$$

B. *Useful energy gain from solar collector*

Useful energy gain from solar collector can be calculated as shown under:

For a flat plate collector the useful energy gain in a day is given by the equation

$$E_{Gain} = A_c\, F' \sum_{i=1}^{i=24} [Hs(i)\,(\tau\alpha) - U_L\,(Tw - Ta(i))] \tag{7}$$

(Using: $E_{Gain} = 0$ when $E_{Gain} < 0$)

The value of ambient temperature and Insolation is taken from [12]

The heat gain for a year is given by

$$E_{Total\ Gain} = \sum_{k=1}^{k=12} E_{Gain}\,(k) \tag{8}$$

V. ECONOMIC ANALYSIS OF DIGESTOR

For evaluating the economic viability of a solar thermal energy system installed for heating of digestor, the savings which will accrue annually and on a long term basis, have been calculated.

A. *Solar Fraction*

Solar fraction is defined as a fraction of the load supplied by solar energy. Monthly Solar Fraction is written as

$$f = \frac{Energy\ collected\ in\ a\ month}{Energy\ lost\ in\ a\ month}$$

(Using: f=1 when f >1.)

Annual solar fraction is defined as

$$f' = \frac{\sum_{n=1}^{n=12} E_{loss}\, f}{\sum_{n=1}^{n=12} E_{loss}} \tag{9}$$

Where n is the month number

B. *Cumulative Solar Savings*

The Cumulative solar savings over a period of n years is obtained by summing the present worth of the annual solar saving and considering the initial down payment made at the time of installation of the solar system.

Considering a solar energy system

1. Assume that the system requires a total investment C of which a fraction f_l is taken as loan. The interest rate on loan is d_l and the loan is to be paid back in equal installments over a period of n years.

Total Investment C= Unit cost of collector x Area of collector, i.e. Total Investment C= C_A x A_c

2. Let the annual energy load to be met be $E_{Total\ Loss}$ and assume that the solar system supplies a fraction f' of this load. This would result in an annual saving of (f' $E_{Total\ Loss}$) of conventional energy. Assume that the cost of this energy is C_f per unit of energy and that it increases at the rate of i_f every year.

3. The solar system requires maintenance cost M per year and this will increase at the rate of i_m every year.

4. The tax deductions are allowed both on the interest component of the annual loan repayment installment as well as

on depreciation of the system. The depreciation is assumed to be at a uniform rate r_d per year. The income tax rate is r_t.

$$\text{Fuel savings} = C_f(1+i_f)^{j-1} f' E_{Total\ Loss} \tag{10}$$

Where C_f is the cost of conventional energy in Rs/MJ, i_f is the rate of increase every year

$$\text{Annual repayment on loan} = \frac{d_l f_l C}{[1-\frac{1}{(1+d_l)^n}]} \quad \text{if } j \le n \tag{11}$$

Where dl is the interest rate on loan, fl is the fraction taken as loan and n is the CSS calculation period

$$\text{Maintenance charges} = (1+ im)\ j-1\ M \tag{12}$$

Where im is the rate of increase in maintenance cost and M is the annual maintenance cost in Rs

Tax deduction on the interest =

$$[1-\frac{(1+d_l)^{j-1}-1}{(1+d_l)^n-1}] r_t d_l f_l C \quad \text{if } j \le n \tag{13}$$

Components of loan repayment:

Tax deduction on depreciation=

$$r_t\ r_d\ C \text{ if } j \le \frac{1}{r_d} \tag{14}$$

Where r_t is the income tax rate and r_d is the depreciation rate

Thus annual solar savings in the year

$$j = C_f(1+i_f)^{j-1} f' E_{Total\ Loss} - \frac{d_l f_l C}{[1-\frac{1}{(1+d_l)^n}]}$$

$$-(1+i_m)^{j-1} M + [1-\frac{(1+d_l)^{j-1}-1}{(1+d_l)^n-1}] r_t d_l f_l C + r_t r_d \tag{15}$$

The cumulative solar saving over a period of n years is obtained by summing up the present worth of the annual solar savings and considering the initial down payment.

Thus Cumulative Solar Saving (CSS) =

$$-(1-f_l)C + C_f f' E_{Totalloss} \sum_{j=1}^{j=n} \frac{(1+i_f)^{j-1}}{(1+d)^j} - \frac{d_l f_l C}{\left[1-\frac{1}{(1+d_l)^n}\right]} \sum_{j=1}^{j=n} \frac{1}{(1+d)^j} - M \sum_{j=1}^{j=n} \frac{(1+i_m)^{j-1}}{(1+d)^j} + r_t d_l f_l C \sum_{j=1}^{j=n} \frac{1}{(1+d)^j} \left[1-\frac{(1+d_l)^{j-1}-1}{(1+d_l)^n-1}\right] + r_t r_d C \sum_{j=1}^{1/r_d} \frac{1}{(1+d)^j} \tag{16}$$

Where d is the market discount rate and n_l is the payback period of loan.

On summing the progression we get Cumulative Solar Saving (CSS) =

$$-(1-f_l)C + \frac{C_f f' E_{TotalLoss}}{(d-i_f)}\left[1-\frac{(1+i_f)^n}{(1+d)^n}\right]$$

$$-\frac{d_l f_l C}{\left[1-\frac{1}{(1+d_l)^{nl}}\right]} \frac{1}{d}\left[1-\frac{1}{(1+d)^{nl}}\right] - \frac{M}{(d-i_m)}\left[1-\frac{(1+i_m)^n}{(1+d)^n}\right]$$

$$+r_t d_l f_l C\left[\frac{(1+d_l)^{nl}-1}{(1+d)^{nl}-1}\right] - \frac{1}{[(1+d_l)^{nl}-1]} \frac{1}{(d-d_l)}\left[1-\frac{(1+d_l)^{nl}}{(1+d)^{nl}}\right]$$

$$+\frac{r_t r_d C}{d}\left[1-\frac{1}{(1+d)^{1/r_d}}\right]$$

For the above equation; $n \ge n_l$, $n \ge (1/r_d)$, $d \ne i_f$, $d \ne i_m$ & $d \ne d_l$

VI. RANGE OF PARAMETERS

TABLE1 INDICATES THE RANGE OF OPERATING PARAMETERS

S.No	Parameter	Value
1.	C_A(Rs/m^2)	1000 to 50000
2.	C_f(Rs/MJ)	0.1 to 10
3.	d	0.05 o 0.25

VII. RESULTS AND DISCUSSION

The results obtained from the mathematical simulation of the solar heated biogas plant are discussed in detail to understand the effect of parameters on the performance of solar collector. Figs.2, 3 & 4 show the variation of CSS as a function of solar collector area for different values of Unit Collector Cost (Cc), Unit Fuel Cost (Cf), and Market Discount Rate (d), respectively.

Fig. 2 shows the variation of CSS as a function of solar collector area for different values of unit cost of collector. It can be observed that CSS increases on decreasing the cost of solar collector and the optimum value of collector area decreases as the collector cost increases.

Fig. 3 shows the variation of CSS as a function of solar collector area for different values of unit fuel cost. It reveals that with the hike in fuel cost, CSS also increases as the fuel saving increases. The optimum collector area also increases with the increase in conventional fuel cost.

Fig. 4 shows the variation of CSS as a function of solar collector area for different values of market discount rates. It can be seen that the maximum value of CSS is obtained at market discount rate of 5%. For all the values of market discount rates, CSS attains maxima at the same value of collector area. It can be concluded that for fixed values of unit collector cost and fuel cost, the optimum value of collector area is not affected by the discount rate.

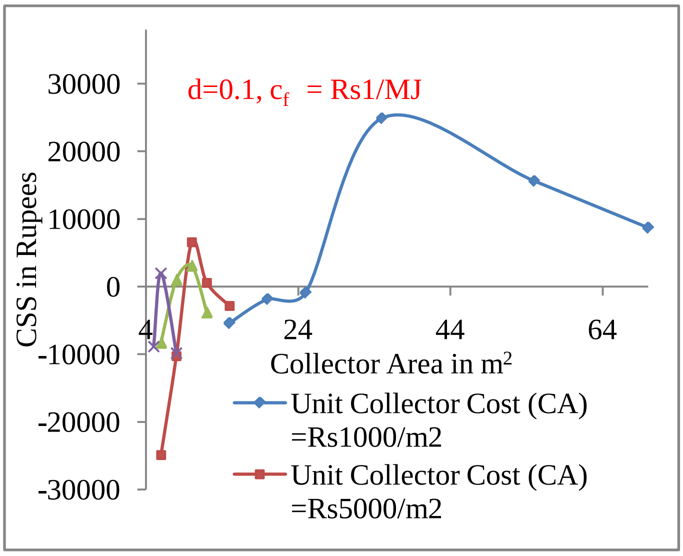

Fig 2 Effect of solar collector area on CSS for different values of unit collector cost for $2m^3$ plant capacity.

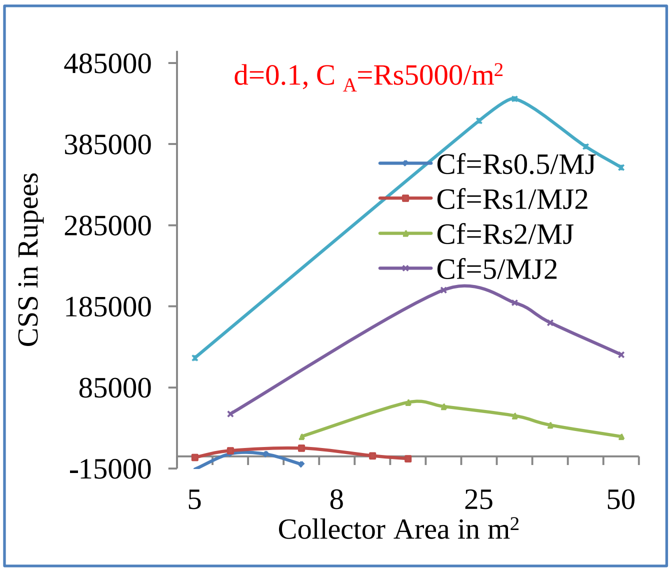

Fig 3 Effect of solar collector area on CSS for different values of conventional fuel cost for $2m^3$ plant capacity.

Fig. 5, 6 & 7 show the optimum value of collector area for different plant capacities for different sets of parameters. Thus one can determine the optimum value of solar collector area for the given set of parameters. Fig 5 shows that the value of optimum area sharply decreases on increasing the unit collector cost and then stays nearly constant. Fig. 6 shows a monotonous increase in optimum value of area when fuel cost increases whereas the values of optimum area is unaffected by the changes in discount rates. The designer can select the optimum value of collector area for the set of operating parameters for a desired plant capacity. A designer can make use of graphs to arrive at the optimal value of collector area for different sets of operating parameters for a given plant capacity. For instance, for a 2m3 plant capacity at CA= Rs 5000/m2, Cf= Rs 1/MJ and d=0.1, one can determine the optimum collector area as 10 m2.

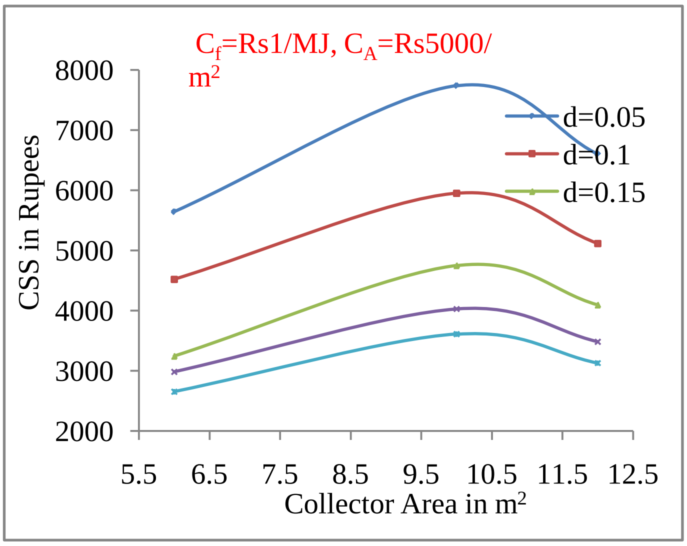

Fig. 4 Effect of solar collector area on CSS for different values of market discount rate for $2m^3$ plant capacity.

VIII. CONCLUSIONS

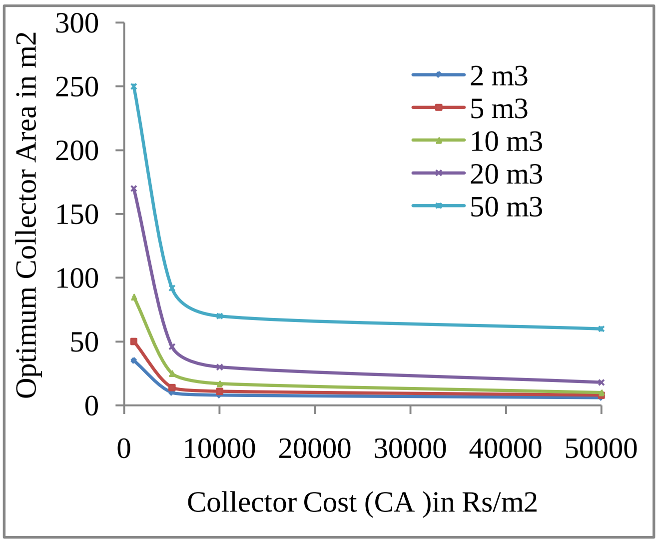

Fig. 5 Optimum value of collector area for different values of unit collector cost for different plant capacities

Thermal and economic analysis of solar heated biogas plant has been carried out using mathematical simulation technique. The effect of operating parameters on Cumulative Solar Saving has been investigated. An optimization of solar collector area has been carried out to evaluate the optimum area for any desired plant capacity and for given values of operating parameters. Following are the conclusions made

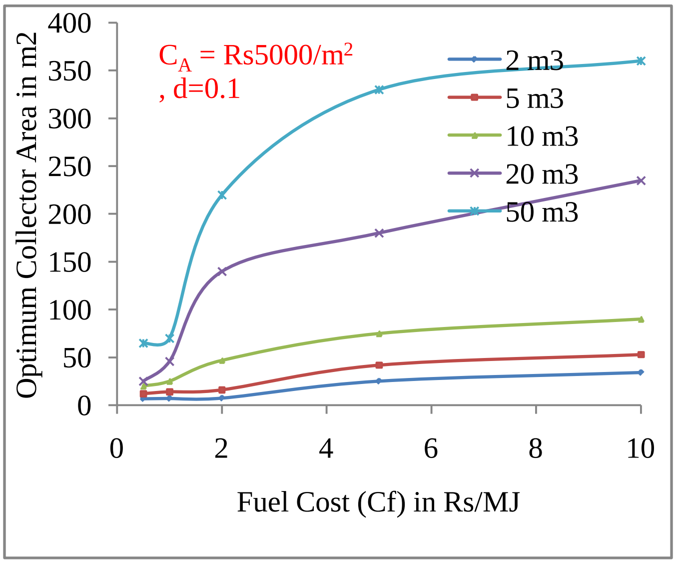

Fig. 6 Optimum value of collector area for different values of fuel cost for different plant capacities.

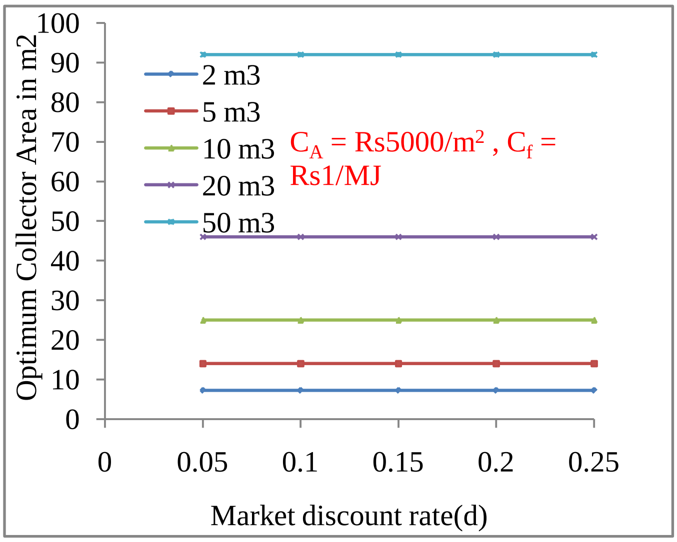

Fig. 7 Optimum value of collector area for different values of market discount for different plant capacities.

1. An increasing collector unit cost results in decreasing Cumulative Solar Saving

2. For fixed values of other parameters and vice versa. The optimum area of solar collector decreases with increase in collector cost.

3. The CSS increases when there is an increase in the conventional fuel cost. The optimum area increases when conventional fuel cost is increased.

4. The cumulative solar saving (CSS) increases with decrease of the market discount rate. The optimum area is not affected by the market discount rate.

5. Design plots have been prepared for the optimum collector area as a function of biogas plant capacity.

6. A procedure to arrive at the optimum value of collector area for given set of values of operating parameters has been developed.

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